The detection of linear polarization in the afterglow of GRB 990510 and its theoretical implications

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Abstract. We present the recent discovery of linear polarization of the optical afterglow of GRB 990510. Effects that could introduce spurious polarization are discussed, showing that they do not apply to the case of GRB 990510, which is then intrinsically polarized. It will be shown that this observation constrains the emission mechanism of the afterglow radiation, the geometry of the fireball and degree of order of the magnetic field. We then present the theoretical interpretations of this observation with particular emphasis on the possibility of observing polarization in beamed fireballs.

INTRODUCTION

Polarization is one of the clearest signatures of synchrotron radiation, if this is produced by electrons gyrating in a magnetic field that is at least in part ordered. For this reason, polarization measurements can provide a crucial test of the synchrotron shock model [11], the leading scenario for the production of the burst and, in particular, the afterglow photons.

Attempts to measure the degree of linear polarization yelded only an upper limit ($\sim 2.3\%$ for GRB 990123 [6]), until the observations on the afterglow of the burst of May 10, 1999. A small but significant amount of polarization was detected ($1.7 \pm 0.2\%$ [2]) ~ 18 hours after the BATSE trigger and confirmed in a subsequent observation two hours later [13].

Even if synchrotron radiation can naturally account for the presence of linearly polarized light in a GRB afterglow, a significant degree of anisotropy in the magnetic field configuration or in the fireball geometry is required. If, in fact, the synchrotron emission is produced in a fully symmetrical set-up, all the polarization components average out giving a net unpolarized flux. The presence of partially ordered magnetic field (in causally disconnected domains) has been discussed by Gruzinov & Waxman [5], however their model overpredicts, in its simplest formulation, the observed amount of polarization. Here we discuss a different possibility,

in which the asymmetry is provided by a collimated fireball observed off–axis, while the magnetic field is tangled in the plane perpendicular to the velocity vector of the fireball expansion. Indeed, the smooth break in the lightcurve of GRB 990510 [7] has been interpreted as due to a collimated fireball observed slightly off–axis.

GRB 990510 MEASUREMENTS

GRB 990510 was detected by BATSE on-board the Compton Gamma Ray Observatory and by the *Beppo*SAX Gamma Ray Burst Monitor and Wide Field Camera on 1999 May 10.36743 UT [8,3]. Its fluence (2.5×10^{-5} erg cm^{-2} above 20 keV) was relatively high [8]. Follow up optical observations started ~ 3.5 hr later and revealed an $R \simeq 17.5$ [1] optical transient (OT). The OT showed initially a fairly slow flux decay $F_\nu \propto t^{-0.85}$ [7], which gradually steepened; Vreeswijk et al. [12] detected Fe II and Mg II absorption lines in the optical spectrum of the afterglow. This provides a lower limit of $z = 1.619 \pm 0.002$ to the redshift, and a γ–ray energy of $> 10^{53}$ erg, in the case of isotropic emission.

We observed the OT associated with GRB 990510 ~ 18 hours after the gamma–ray trigger at the ESO VLT-Antu (UT1) in polarimetric mode, performing four 10 minutes exposures in the R band at four angles (0°, 22.5°, 45° and 67.5°) of the retarder plate [2]. The average magnitude of the OT in the four exposures was $R \sim 19.1$. Relative photometry with respect to all the stars in the field was performed and each couple of simultaneous measurements at orthogonal angles was used to compute the points in Fig. 1 (laft panel) (see [2] for details). The parameter $S(\phi)$ is related to the degree of linear polarization P and to the position angle of the electric field vector ϑ by:

$$S(\phi) \;=\; P \cos 2(\vartheta - \phi). \tag{1}$$

P and ϑ are evaluated by fitting a cosine curve to the observed values of $S(\phi)$. The derived linear polarization of the OT of GRB 990510 is $P = (1.7 \pm 0.2)\%$ (1σ error), at a position angle of $\vartheta = 101^\circ \pm 3^\circ$. Fig. 1 (left panel) shows the data points and the best fit $\cos\phi$ curve. The statistical significance of this measurement is very high. A potential problem is represented by a "spurious" polarization introduced by dust grains interposed along the line of sight, which may be preferentially aligned in one direction. The normalization of the OT measurements to the stars in the field already corrects for the average interstellar polarization of these stars, even if this does not necessarily account for all the effects of the galactic ISM along the line of sight to the OT (e.g. the ISM could be more distant than the stars, not inducing any polarization of their light). To check this possibility, we plot in Fig. 1 (right panel) the degree of polarization vs. the instrumental position angle for each star and for the OT. It is apparent that, while the position angle of all stars are consistent with being the same (within 10 degrees), the OT clearly stands out. The polarization position angle of stars close to the OT differs by $\sim 45^\circ$ from the position angle of the OT. This is contrary to what one would expect if the polarization of the OT

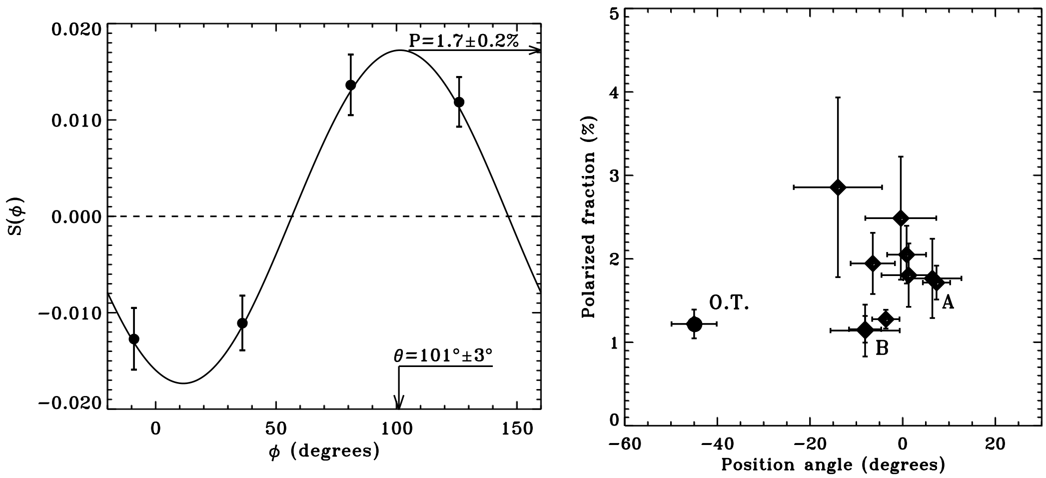

FIGURE 1. Left Panel: our polarization data taken at four different position angles ϕ are fitted with a cosine curve. The amplitude of this curve corresponds to the degree of linear polarization, and its maximum to the polarization position angle. Data are normalized to the average of the stars in the same field. **Right Panel**: The unnormalized degree of polarization vs. the instrumental polarization position angle of the stars in the field and the optical transient. The optical transient clearly stands out (P $= 1.2 \pm 0.2\%$). The two stars closest to the OT are labelled A and B.

were due to the galactic ISM. Polarization induced by absorption in the host galaxy can be constrained to be $P_{host} < 0.2\%$, due to the lack of any absorption in the optical filters in addition to the local value (see [2] for more details). We therefore conclude that the OT, even if contaminated by interstellar polarization, must be intrinsically polarized to give the observed orientation.

POLARIZATION FROM BEAMED FIREBALLS

We consider a slab of magnetized plasma, in which the configuration of the magnetic field is completely tangled if the slab is observed face on, while it has some some degree of alignment if the slab is observed edge on. Such a field can be produced by compression in one direction of a volume of 3D tangled magnetic field [9] or by Weibel instability [10]. If the slab is observed edge–on, the radiation is therefore polarized at a level, P_0, which depends on the degree of order of the field in the plane. If the emitting slab moves in the direction normal to its plane with a bulk Lorentz factor Γ, we have to take into account the relativistic aberration of photons. This effect causes photons emitted at $\theta' = \pi/2$ in the (primed) comoving frame K' to be observed at $\theta \sim 1/\Gamma$ (see also [10]).

We assume that the fireball is collimated into a cone of semi–aperture angle θ_c, and that the line of sight makes an angle θ_o with the jet axis. As long as $\Gamma > 1/(\theta_c - \theta_o)$, the observer receives photons from a circle of semi-aperture angle

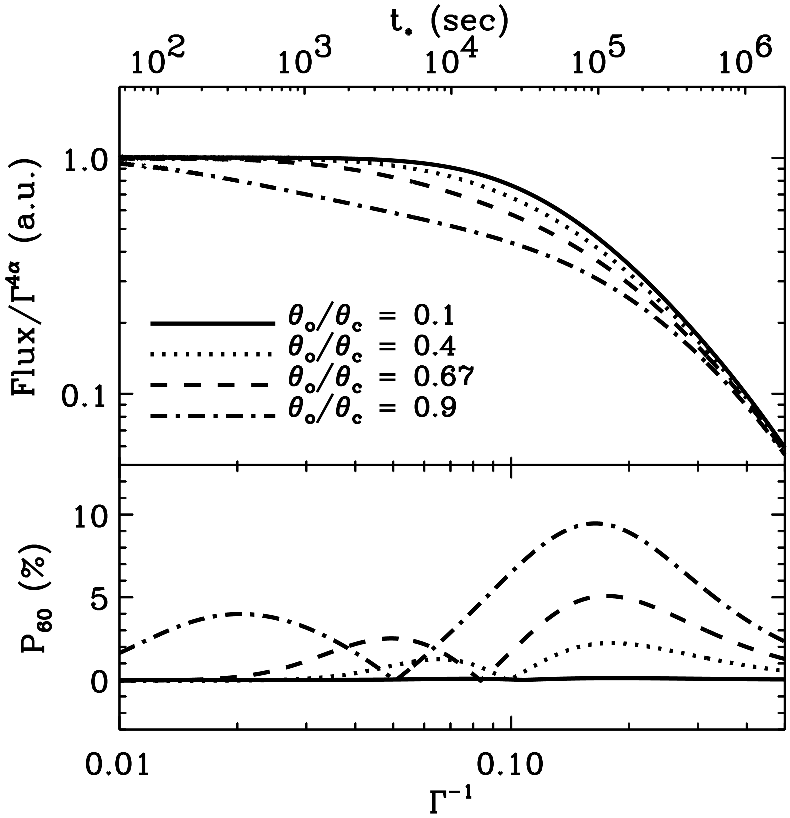

FIGURE 2. Lightcurves of the total flux (upper panel) and of the polarized fraction (bottom panel) for four different choices of the ratio θ_o/θ_c. The cone aperture angle $\theta_c = 5°$, while θ_o is the viewing angle. The higher the ratio θ_o/θ_c, the higher the polarized fraction due to the increase of the asymmetry of the geometrical setup. The actual value of the observed polarization depends linearly upon P_0. In this figure we assumed $P_0 = 60\%$. The lightcurve of the total flux assumes a constant spectral index $\alpha = 0.6$ for the emitted radiation. Note that the the highest polarization values are associated with total flux lightcurves steepening more gently. To calculate the values of the upper x–axis (t$_\star$), we assumed $(t_\star/t_0) = (\Gamma/\Gamma_0)^{-8/3}$ with $t_0 = 50$ s and $\Gamma_0 = 100$.

$1/\Gamma$ around θ_o. Consider the edge of this circle: radiation coming from each sector is highly polarized, with the electric field oscillating in radial direction (see [4] for more details). As long as we observe the entire circle, the configuration is symmetrical, making the total polarization to vanish. However, if the observer does not see part of the circle, some net polarization survives in the observed radiation. This happens if a beamed fireball is observed off–axis when $1/(\theta_c + \theta_o) < \Gamma < 1/(\theta_c - \theta_o)$.

At the beginning of the afterglow, when Γ is large, the observer sees only a small fraction of the fireball and no polarization is observed. At later times, when Γ becomes smaller than $1/(\theta_c - \theta_o)$, the observer will see only part of the circle centered in θ_o: there is then an asymmetry, and a corresponding net polarized flux. To understand why the polarization angle in this configuration is horizontal, consider that the part of the circle which is not observed would have contributed to the polarization in the vertical direction. At later times, as the fireball slows down

even more, a larger area becomes visible. When $\Gamma \sim 1/(\theta_c + \theta_o)$, the dominant contribution to the flux comes from the upper regions of the fireball which are vertically polarized. The change of the position angle happens when the contributions from horizontal and vertical polarization are equal, resulting in a vanishing net polarization. At still later times, when $\Gamma \to 1$, light aberration vanishes, the observed magnetic field is completely tangled and the polarization disappears.

Figure 2 shows the result of the numerical integration of the appropriate equations (see [4] for the detailed discussion). As derived in the above qualitative discussion, the lightcurve of the polarized fraction shows two maxima, with the position angle rotated by 90° between them. It is interesting to note the link with the lightcurve. The upper panel of Fig. 2 shows the lightcurve of the total flux divided by the same lightcurve in the assumption of spherical geometry. As expected, the lightcurve of the beamed fireball shows a break with respect to the spherical one. A larger off–axis ratio produce a more gentle break in the lightcurve, and is associated with a larger value of the polarized fraction. The behaviour of the total flux and of the polarization lightcurves allow us to constrain the off–axis ratio ϑ_o/ϑ_c, but is insensitive to the absolute value of the beaming angle ϑ_c. Therefore, even if we could densely sample the polarization lightcurve, the beaming angle could be derived only assuming a density for the interstellar medium, i.e. a relation between the observed time and the braking law of the fireball. On the other hand, the detection of a 90° rotation of the polarization angle of the afterglow would be the clearest sign of beaming of the fireball, expecially if associated with a smooth break in the lightcurve. Polarimetric follow up of afterglows is hence a powerful tool to investigate the geometry of fireballs.

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